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Application and Evaluation of Different Fuel Element Failure Criteria to FBR Hypothetical Accidents

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Abstract

10 different approaches on LMFBR hypothetical accident fuel element failure prediction as described in the open literature have been selected, analyzed, programmed, and applied to different transient cases. The paper shortly reviews the basis of the models and compares the results obtained. Calculations are based on URANUS analyses of Transient Overpower and Coolant Blockage events. Model evaluation shows that an universal approach, taking into consideration all the different modes of failure, is not yet available. Good agreement for model-to-model or model-to-experiment may be achieved in well defined cases. Further modelling effort ist necessary in that special field.

1. Introduction

In collaboration with the Whole Core Accident Codes (WAC) Group of the Commission of the European Communities (CEC), a literature survey on fuel element failure events during hypothetical transient overpower (TOP) or loss-of-coolant (LOF) accidents has been performed. Based on this study, 10 models have been selected and programmed, differing in their formulations from simple empirical correlations up to "mechanistic" approaches. Microphysical models will be investigated in the future.

All of the models try to predict key phenomena during the development of hypothetical LMFBR accident sequences: mode of failure, failure location, and failure time. Most of the criteria are based on or devoted to specific types of tests. The idea of the present work thus is to investigate, whether the present models may be used in a more general way of application, beyond the experiments they had been fitted to, and with other fuel element codes than those used for the original applications. A modular subprogram-package FAILRE has been written which easily may be coupled to transient fuel element codes like URANUS /1/ or whole core codes (eg. EAC). Simple stand-alone calculations can be performed as well.

2. Modes of Failure

For better characterization of the events related with TOP, LOF or LOFTOP type accidents, 7 different situations probably leading to failure have been defined ("failure mechanisms"):

FM 1 Coolant boiling at cladding surface
FM 2 Cladding melting due to contact with molten fuel (melt-through)
FM 3 Failure due to fuel evaporation pressure build-up
FM 4 Different thermal expansion of fuel and cladding
FM 5 Fission gas release & pressure build-up due to fuel melting
FM 6 Fission gas release & pressure build-up prior to fuel melting
FM 7 Transient fuel swelling

In most cases, fuel failure will not be caused by a single mode of failure, but by a combination of different pathes. The two main influences on path-to-failure are: -- pretransient conditions and -- type of accident.

The characterization of the pretransient conditions still remains a challenge to fuel element structural analysis, although much progress has been made over the past years. Cladding failure prediction during a transient requires a detailed knowledge about the pretransient history. Not only radiation damage of the clad, but also the structural changes in the fuel, cracking, relocation, central void formation, swelling, resintering, produced fission gas and extend of gas bearing zones, etc., are quite important. Fuel-cladding mechanical and chemical interactions have to be taken into account. Cladding reannealing, irradiation hardening, Helium embrittlement, and fuel adjacency effects will occur. Similar problems exist for the description of fast accident sequences.

With the present knowledge on all these effects, the determination of fuel and clad conditions, in particular with high burnup, remains difficult. A recent code comparison project /2/ thus concluded: "it was found, that the codes produce significantly different results for key quantities such as cladding stress, strain, and pin failure conditions". This, in particular, is valid for simple fuel element codes often applied to whole core analyses or for the description of special experiments. The authors feel that correct failure prediction is only possible by using a consistent physically based fuel element structural analysis, allowing for the determination of all necessary boundary conditions.

3. Models Selected

Pin failure models may be divided in the following way:

A - Empirical correlations
B - Correlations based on mechanical descriptions
    B1 - Strain based criteria
    B2 - Stress based criteria
C - Microphysical models

From the open literature, 10 models have been selected which are assumed to be typical examples for the empirical and mechanically based criteria:

- Melt Fraction Criteria (A: MFC-I, MFC-II)
- Melt-Through Criterion (A: MTC)
- Failure Potential Criterion (A: FPC)
- Integrated Strain Rate Method (B1: ISRM)
- Strain Failure Limit Correlation (B1: SFLC)
- Conservative Strain Criterion (B1: CSC)

- Transient Failure Strain Criterion (B1: TFSC)
- Life Fraction Rules, Dorn & Larson-Miller (B2: LFR-DP, LFR-LMP)

A discussion of microphysical models will be given elsewhere. Detailed descriptions of all criteria mentioned including references are given in /3/. In the following, only a very short overview is presented for type A, B1 and B2 models.

A. Melt Fraction Criteria are based on the idea that a significant cladding loading will occur if the fuel melt front reaches the outer, gas-bearing zones, causing a sudden fission gas release. Consequently, these criteria may only be used, if failure mode FM 5 is dominant. Both criteria are very crude approximations. Different melt fraction thresholds (30%,50%,80%) are applied for MFC-I to consider the pretransient power history. MFC-II uses a direct comparison between calculated melt-radii and calculated fuel structural zones. Since no fuel structural analysis is necessary except a temperature calculation, they are widely used in whole core codes. However, there is no doubt that temperature calculations without structural analysis (gap size, gap conductance!) are useful for very fast TOPs only. The Melt-Through Criterion is based on observations and theoretical evaluation of contact temperature theories. It can be shown that with high cladding temperatures (>1200K) and high fuel melt fraction (>80%), a complete clad melt-through can occur when a sudden contact (eg. break-away of the outer fuel ring) takes place (FM2). The Failure Potential Criterion is a cumulative damage approach, based on 12 TREAT TOP-tests. If the FP-value exceeds 1, failure is predicted. The correlation includes a dependence on enthalpy upset in the noncolumnar grain region, cladding burst strength, fuel and cladding structural features (eg. densities, gap size), and time into transient. The correlation suffers from many applicability limitations concerning burnup, pretransient power, fluence, and type of transient. On the other hand, similar drawbacks should be expected for most criteria because of the small data basis, but often are not mentioned.

B1. Strain based criteria use a comparison between calculated cladding strains and strain failure thresholds. These thresholds are either burnup-dependent only (ISRM, CSC, typically 1-5% plastic deformation), or based on correlations, taking into account clad temperature, temperature rate, fluence, etc. (SFLC, TFSC). Whereas the Integrated Strain Rate Method uses an empirical law to calculate the cladding deformation (based on temperature and clad inner radial loading, thus incorporating some features of the stress based correlations), the other criteria use strain histories as calculated by typical fuel element thermo-mechanical analyses. Experience with both the Strain Failure Limit Correlation and the Transient Failure Strain Criterion shows that very low threshold strains (<1%) are obtained. Two reasons seem to be responsible for such a behaviour: The data basis for the SFLC shows a tremendous scattering, resulting in a mean error of 46% and a maximum error of 195% for the correlation. The TFSC shows an extreme sensitivity on low temperature rates, leading to failure thresholds <0.5% even for fresh cladding material. Consequently, very early in a transient clad failure is predicted. In spite of these drawbacks, the authors feel that the introduction of path-dependent thresholds is the best way if strain criteria shall be used. Further investigations into such models therefore are foreseen.

B2. Stress based criteria either use a direct comparison between calculated maximal stresses and fixed or path-dependent failure stress thresholds, or determine life fraction increments via a relation between stress rupture lifetime measurements and transient time (eg. Life Fraction Rule). Larson-Miller and Dorn-Parameters are typical correlations accomodating experimental stress rupture life data. There are some arguments whether LFRs may be applied to typically fast loading histories during reactor transients. However, during the last years many contributions showed that reasonable results may be obtained. For the present work, both the LFR with Dorn-Parameter and with Larson-Miller-Parameter are applied. Dorn includes a dependence on temperature rate and fluence, whereas Larson-Miller uses a set of different parameters for different fluence ranges.

Besides practical experience with these 10 models (see §4), theoretical evaluation already shows how difficult and uncertain the applications will be. All correlations suffer from:

- small and uncertain data basis
- non-prototypic in-pile test conditions (geometry and irradiation)
- non-prototypic out-of-pile tests
- uncertainties of the fuel element codes applied when fitting the models to experimental evidence
- no or only small basis for extrapolations
- material dynamics is not yet fully understood.

Most drawbacks could be avoided by conducting more prototypical experiments and by improving the codes applied. However, the last point mentioned requires detailed new work and is directly connected with the progress made in the development of microphysical models.

4. Test Calculations

The following calculations have been carried out with the URANUS code system /1/ and the newly developed FAILRE system. 3 hypothetical overpower transients are analyzed, based on earlier work /2,4/, with 5¢/s, 50¢/s and 5$/s reactivity insertion rates. In addition, 2 pins of the TREAT-H3 experiment are discussed, and some results of recent applications to coolant blockage experiments are given. The calculations prove that the new system works fast and reliable. The evaluation of the correlations implemented, however, shows that additional work still has to be carried out.

The calculations for the three hypothetical transients are based on a common preirradiation phase. Some 3% burnup are reached in 161 days with a maximum rating of 41 kW/m. More than 50% of the fission gas is retained in the fuel at start of the transients. Transient times investigated are up to 700 ms (5$/s), 6s (50¢/s and 60s (5¢/s). For the 5$/s case, figs. 1, 2 give an overview on most relevant results; similar plots with other time-scale are obtained for the other cases. Table 1 gives an overview on the different failure criteria. For the fastest case better agreement can be reached than for the slower cases: this behaviour has already been discussed in /2/. Most of the predicted first failure times for the 50/s case lie in a relatively narrow range between 540 and 610 ms. The stress-dependent criteria like LMP-DP or ISRM (which uses the stress as an input) predict later failure between 640 and 700 ms. The TFSC lies completely out of range (200 ms). As expected, in most cases first failure is predicted in axial positions between mid-core and 75% height. So for the medium transient: most results are obtained for the upper part of the core, typical times are between 4.2 and 5s. Again stress-dependent criteria need some more time; TFSC and SFLC are out of range. For the slow case, 2 additional locations are predicted by some criteria at the lowest and uppermost sections. Failure times are from 66 to 80s; TFSC again gives unreliable results. It is obvious that slow cases are more difficult to predict because of the many events taking place in the fuel during these comparably long times. In an integral sense, results obtained for the 3 cases are not so bad if some additional interpretation concerning data basis and type of model is introduced. Table 1 thus distinguishes between reliable results (thick letters) and other; this is, however, due to the user's experience.

There are, naturally, many influences on the results which are directly affected by the use of proper material data for fuel and cladding. Some additional calculations therefore have been made using mechanical data other than in the standard case ("S") calculations discussed above. Test cases "I, II, III" use varied yield stress data, which however still are in the typical range published (± 20%). Nearly no influence was detected so far type A empirical criteria are concerned. Stress and strain dependent criteria are significantly affected. Figs. 3, 4 show as an example the development of the transient permanent clad deformation and LFR-DP life fraction plots. For better comparison, results of other codes (from /2/) are introduced, now enveloped by the 2 URANUS results for cases "S" and "III". Failure times of the other criteria are affected in similar kind.

Failure criteria should not predict failure if there was none. This very trivial statement was investigated by applying all criteria to 2 rods of the TREAT-H3 experiment (test-pin and driver rod). Low FP-values (<0.24), low melt fractions (<7%), low life fraction values ($<10^{-3}$ DP; $<10^{-4}$ LMP), and very low permanent strains resulted. However, both SFLC and TFSC predict failure at 0.15% permanent cladding deformation. These failure strains are much to low and confirm the problems already revealed in §3 and with the 3 TOP transients.

All criteria were applied to a special Mol 7C coolant blockage experiment. Because of the applicability limitations, LFR-LMP and ISRM were not investigated. For this type of experiment, failure mode FM 1 is the most probable path to failure. Failure indication via MFC or MTC cannot be expected. During the transient, the coolant mass flow rate is continously reduced inside the blocked area. Consequently, partial coolant boiling, then dryout and clad failure occurs. In the calculations, first failure is predicted by the FPC at 4.2s after triggering, approx. 0.2s after first reaching of evaporation temperature. 6.1s after triggering nearly the complete blockage has exceeded dry-out conditions. At this time LFR-DP indicates failure, followed by TFSC at 6.2s. At 6.6s clad melting starts; at 7s first direct clad melting has occured, together with failure prediction by SFLC. It turns out in this special case that SFLC and TFSC are now able to predict failure in good agreement with experimental evidence.

5. Conclusions

There was only 1 criterion in this exercise which always could be applied and allways predicted failure at time and position to be expected: The FPC.
8 criteria out of 10 give reasonable results in more than 4 of the 6 cases investigated. FPC, MFC-II, LFR-DP, MTC and CSC seem to work in a reliable way; SFLC and TFSC are not recommended. This result is better than expected. However, the many problems related with the application, the uncertainties of the material data, the missing consistent validation of criteria and code versus experimental results, the scattering results (in particular for slow transients), and the more general problem that there will always be a combination of different pathes to failure in real cases, are severe implications. None of the criteria is a universial one which could be used for all different types of transient and all pathes to failure. A lot of engineering judgement is still necessary for the interpretation of the results. Further work in the field thus seems to be necessary, aiming into the direction of more universal models on one hand, and to microphysical models on the other.

6. Acknowledgement

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7. References

/1/ T. Preusser, K. Lassmann, Current Status of the Transient Integral Fuel Element Performance Code URANUS, SMiRT-7, Sect. C4/3, Chicago, 1983.

/2/ J.M. Kramer, T.H. Hughes, Comparison and Evaluation of Four Transient Fuel Behaviour Codes, Top. Meeting Reactor Safety Aspects of Fuel Behaviour, Sun Valley, 1981.

/3/ T. Preusser, Report rtda-98-83, Technical University Darmstadt, 1983.

/4/ T. Preusser, K. Lassmann, Application and Results of the Transient Integral Fuel Element Performance Code URANUS to FBR Hypothetical Accident Analysis, SMiRT-7, Sect. C4/4, Chicago, 1984.

Criterion	5 $/s		50 ¢/s		5 ¢/s	
	Position %	Time ms	Position %	Time s	Position %	Time s
FPC	69 - 75	590	69 - 75 31	4.7 4.5	69 - 75 31	71 58
MFC-I	47 - 64 14	579 574	47 - 69 14, 100	4.9 4.4	100 14	66 69
MFC-II	47 - 69	540	47 - 69	4.4	64 14	78 75
LFR-LMP	×	×	47 31	6.0 4.5	47 31	80 67
LFR-DP	64 - 75	680	75 100	4.6 4.0	×	×
ISRM	75	700	64 - 69	5.9	75 100	80 67
SFLC	×	×	14 - 75	1.8	47 - 75 100	69 37
MTC	64 - 69	609	64	4.9	×	×
CSC	64 - 69 47	546 524	64 69 47	4.2 4.0	69 47	74 71
TFSC	31 - 75	200	31 - 75	1.3	47 - 75	10

Table 1: Overview on first failure predictions by different criteria. x = Criterion not applicable.
— = No failure. Thick letters = Reliable results.

Section	1	2	3	4	5	6	7	8
% rel. Height	0	14	31	47	64	69	75	100

Table 2: Axial positions for all figures 1 - 4.

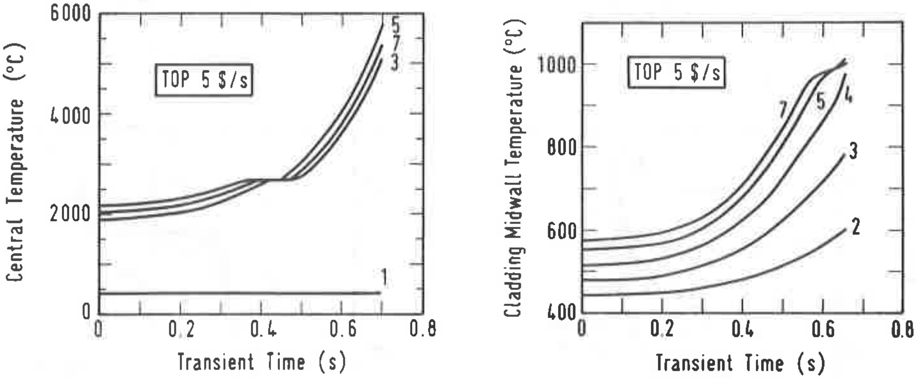

Fig. 1a,b: Temperature development fuel (left) and clad (right) versus transient time, 5 $/s TOP. URANUS-calculations.

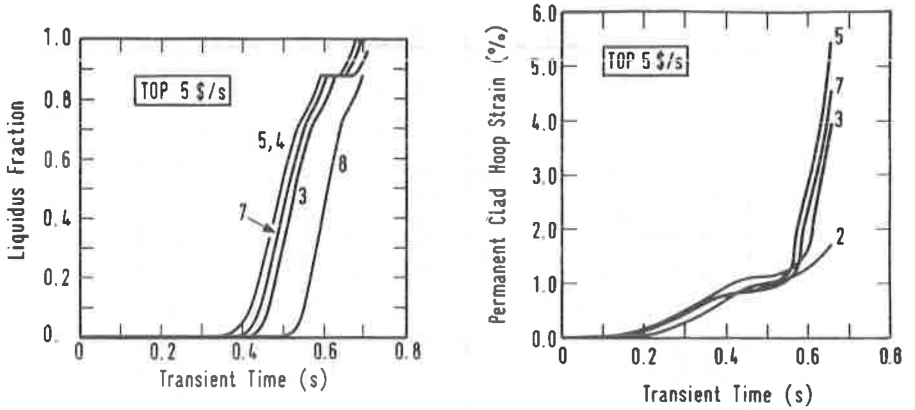

Fig. 2a,b: Fuel liquidus fraction (left) and clad strain (right) versus transient time, 5$/s TOP. URANUS-calculations.

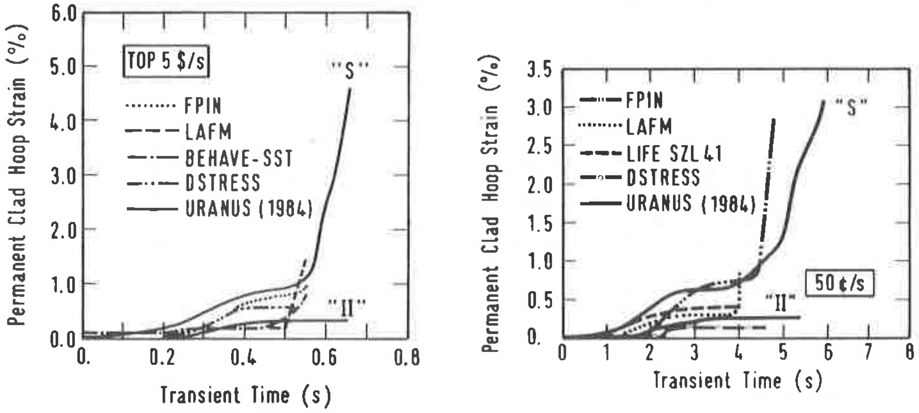

Fig. 3a,b: Comparison of calculated clad strains, 5 $/s & 50 ¢/s. Different codes, different material data. Section 7.

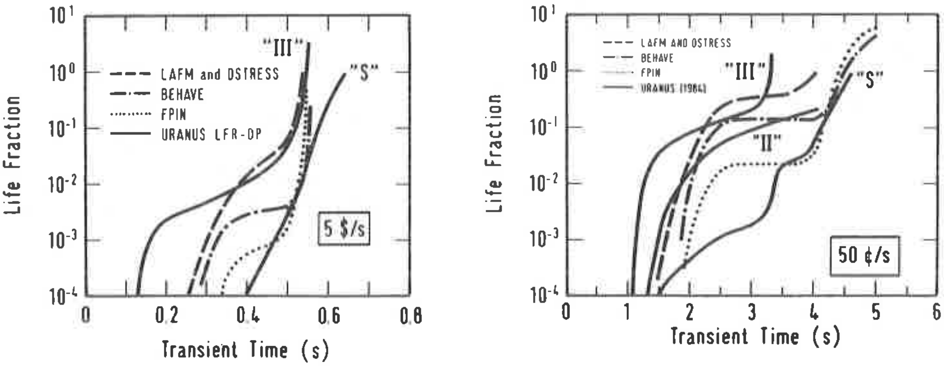

Fig. 4a,b: Comparison of calculated Life Fractions, 5 $/s & 50 ¢/s. Different codes, different material data. Section 7.